Advanced Sensors for Real-time control of Advanced Natural Gas Reciprocating Engine Combustion

S. H. Sheen, H. T. Chien and A. C. Raptis

Argonne National laboratory

April 23-24,2002

Project Objectives

To develop advanced sensors and control system for real-time combustion monitoring of advanced natural-gas reciprocating engines, proposed sensors include:

- NOx emission sensor
- Natural-gas composition sensor

Technical Approaches

- NOx sensor based on ion-mobility spectrometry (IMS)
- Natural-gas composition sensor based on acoustic techniques, measurements of speed-of-sound and acoustic relaxation spectroscopy

Project Team

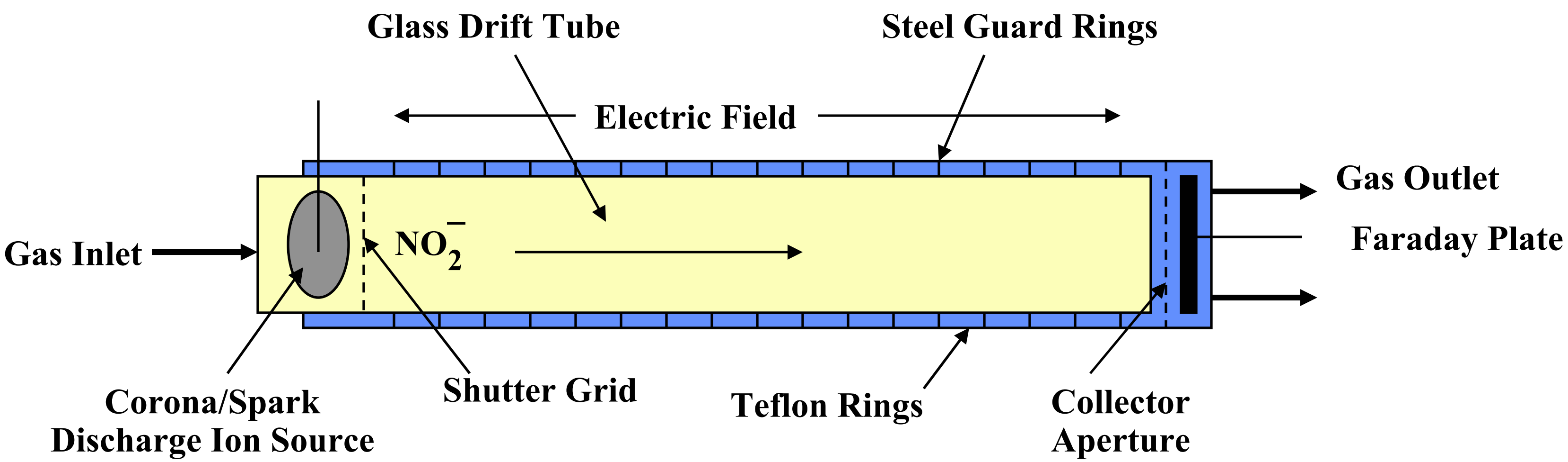
- Argonne National Laboratory
  – Sensor development
- Northwestern University
  – Theoretical modeling
- Commercial Electronics (Broken Arrow, OK)
  – Control electronics

Major Tasks and Schedule

- Establish an acoustic model for fuel-composition prediction -------------09/30/01
- Develop and test non-radioactive IMS sensor for detecting NOx ----------06/30/02
- Develop and test acoustic natural-gas composition sensor -----------------09/30/02
- Complete field tests of sensors ---09/30/03

IMS Sensor for NOx

Basic Design of an IMS



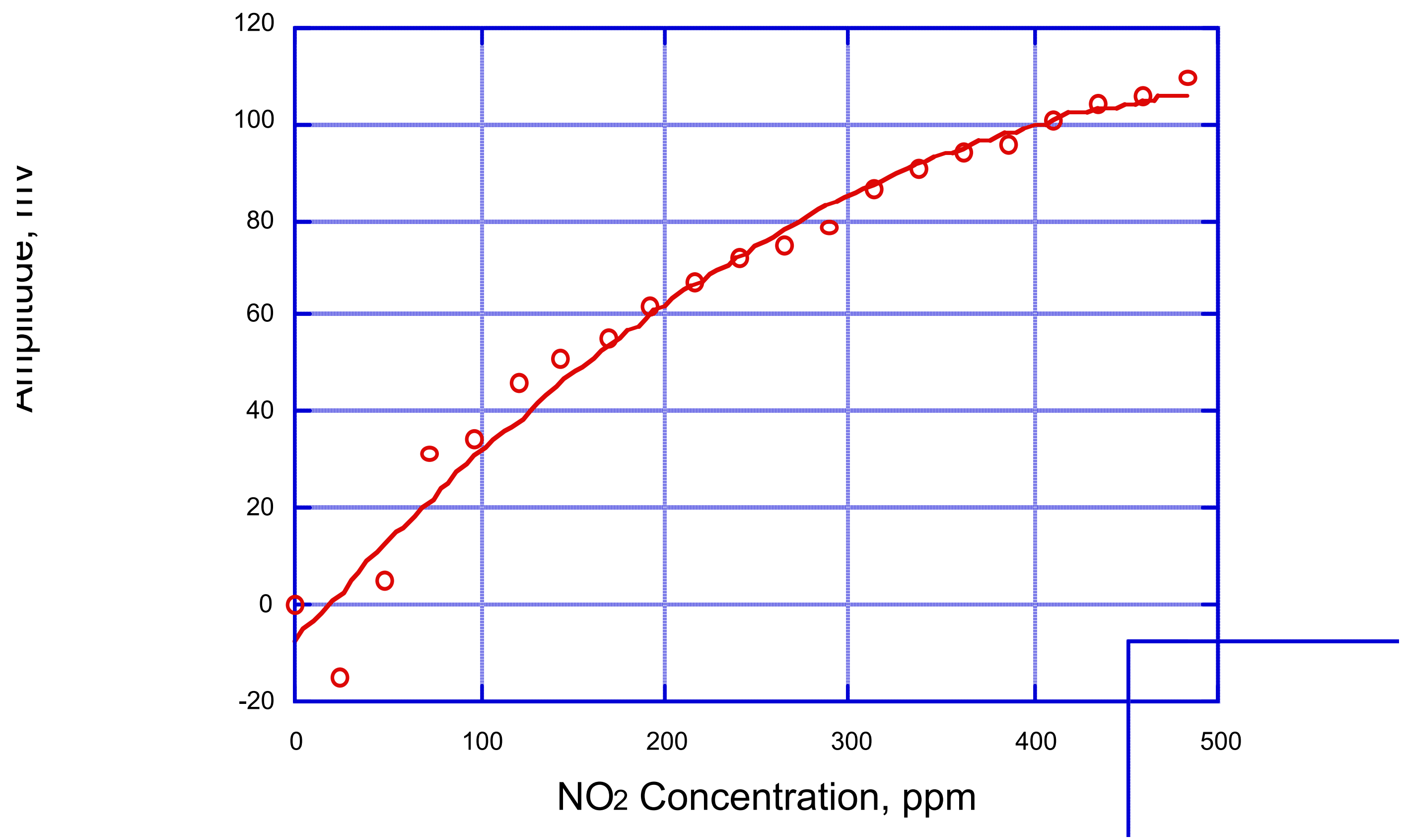
Electron Affinity- Negative Ion Formation

Molecule	Electron Affinity, eV
CO	1.37
CO_2	< 0
Propane	< 0
Propene	< 0
Toluene	< 0
H_2	< 0
H_2O	1.2
NO	**0.026**
NO_2	**2.273**
N_2	< 0
O_2	0.451
SO_2	1.107

Test Gases

- Carrier gas
  - (Gas C-1): 23.6 ppm SO_2, 121.2 ppm H_2, 398 ppm CO, 8.1% O_2, 10% CO_2, and N_2 the balance
  - (Gas C-2): Dry N_2
- Sample gas
  - (Gas S-1): 483 ppm NO_2 in dry nitrogen
  - (Gas S-2): 509 ppm NO, 515 ppm NO_x, and N_2

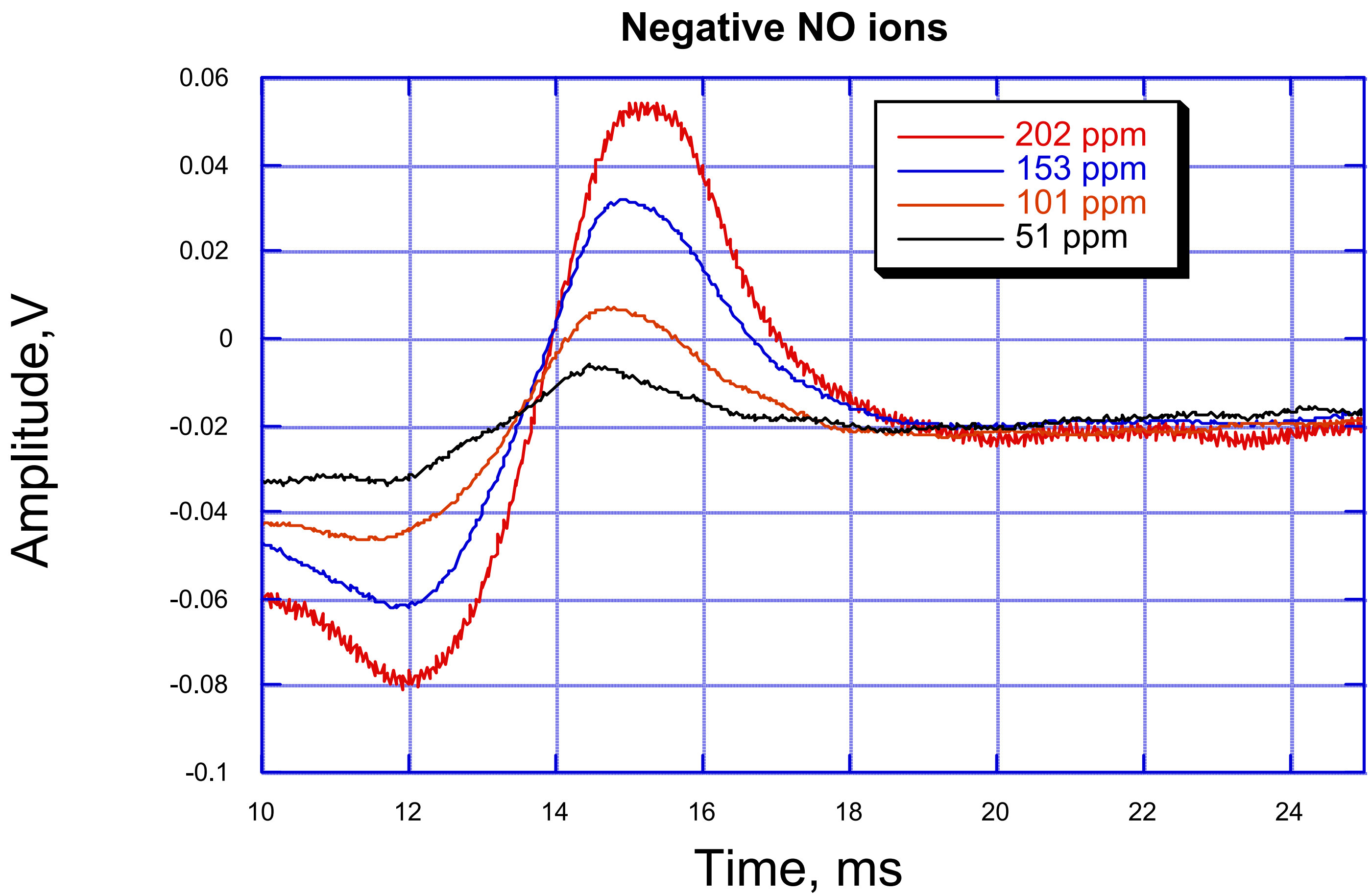
Peak Amplitude as a Measure of NO_2 concentration (Gases: C-2 and S-1, Sensitivity: 2 nA/V)



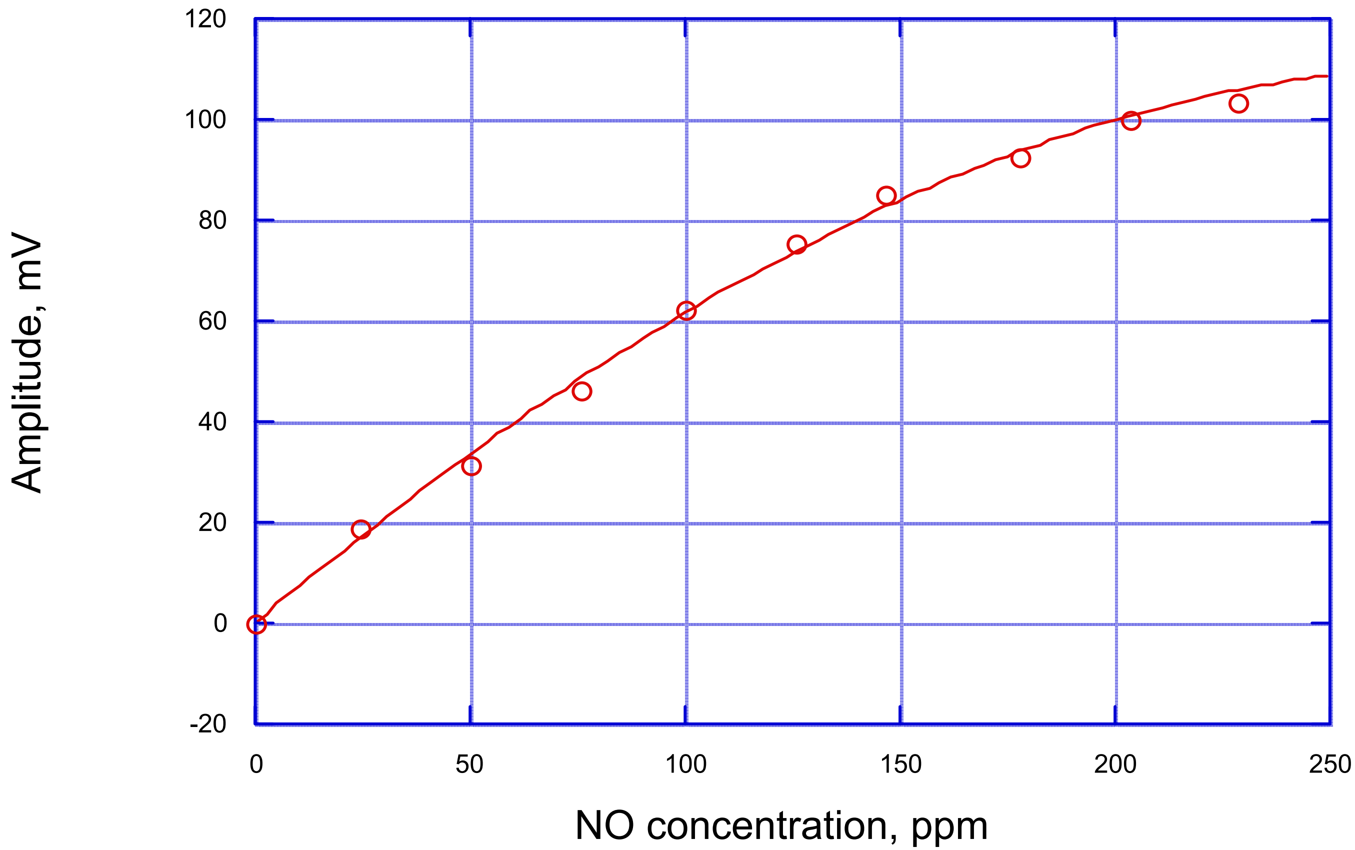
ARGONNE

50 YEARS

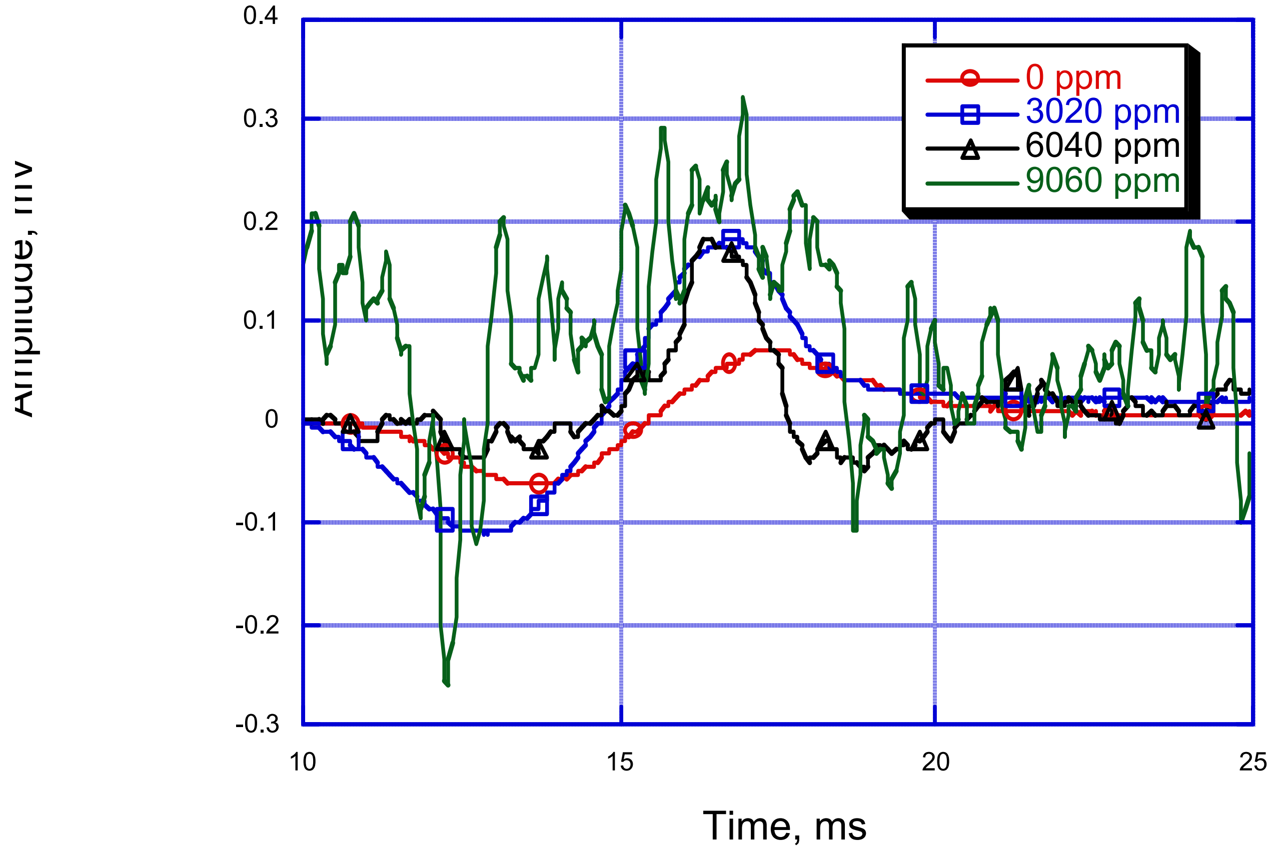
Negative NO Peaks of Different Concentration (Gases: C-2 and S-2, Sensitivity: 2nA/V)



Peak Amplitude as a Measure of NO concentration
(Gases: C-2 and S-2, Sensitivity: 1nA/V)

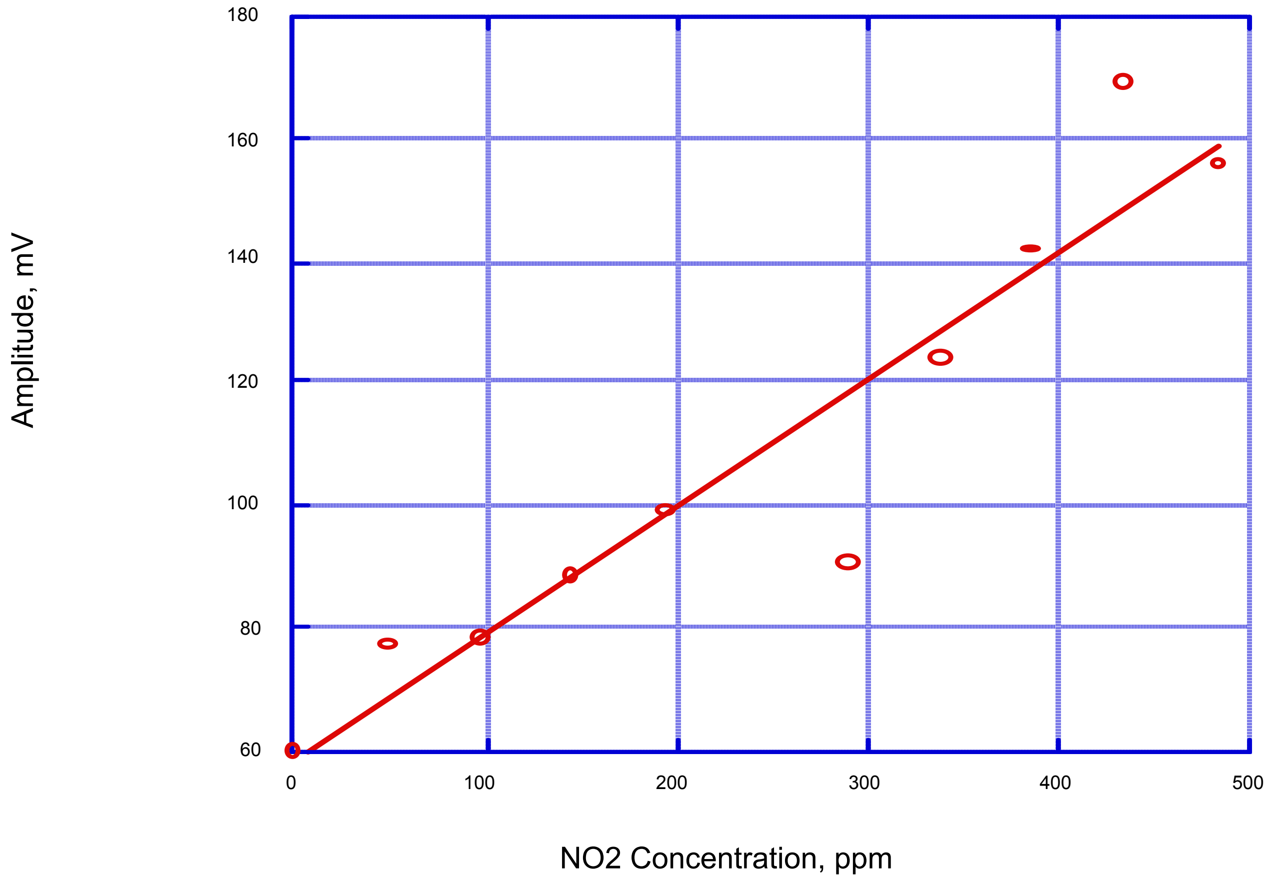


Water Vapor Effect on NO_2 Peaks



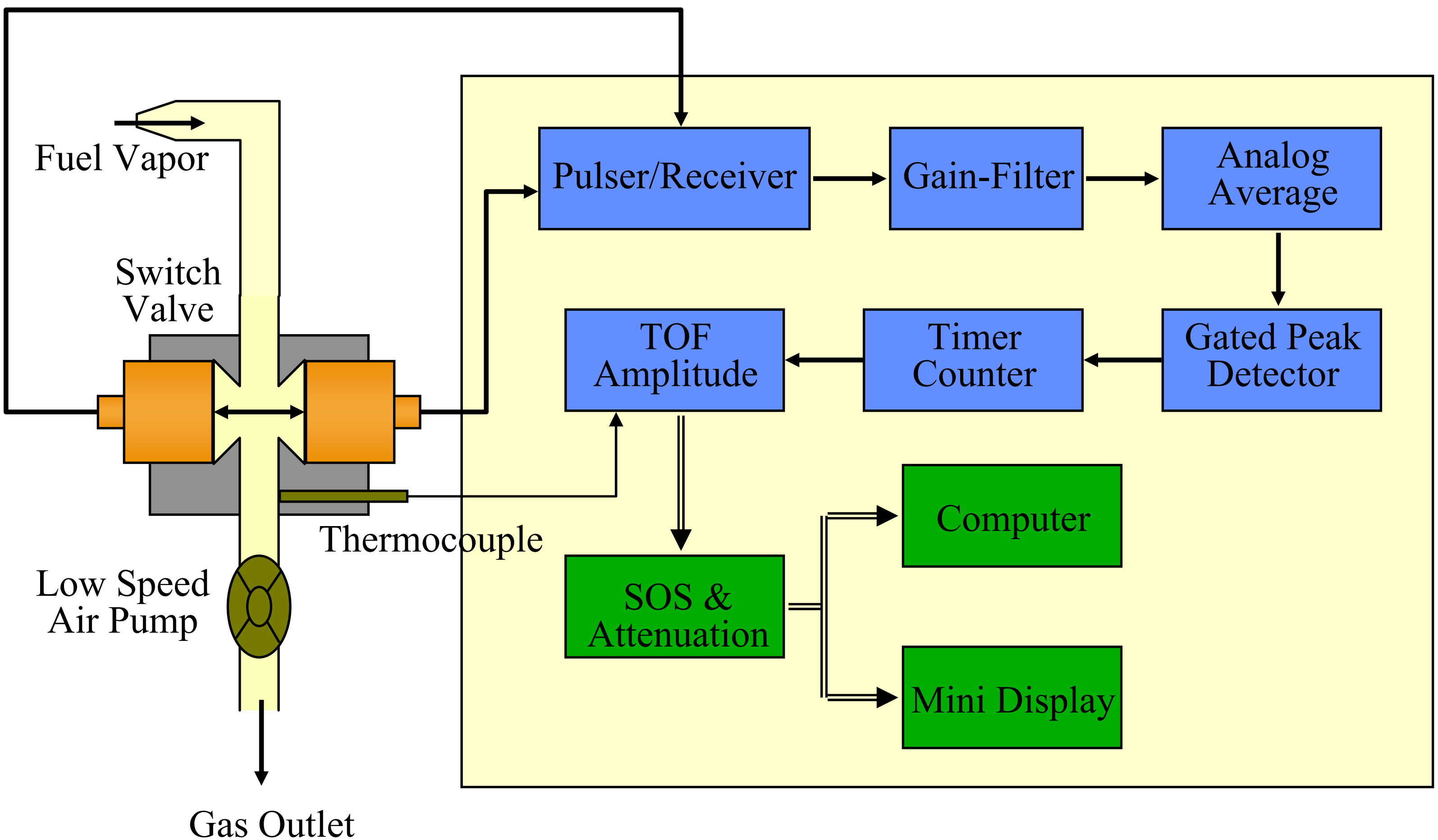
ARGONNE

Use of Thermoelectric Cold Plate to Reduce Water-vapor Content (Gas temperature in IMS: 0°C, Gas:C-2, S-1 and 1% water vapor)



Acoustic Natural-gas Composition Sensor

Basic Design of SOS Gas Sensor



Natural Gas Composition Sensor

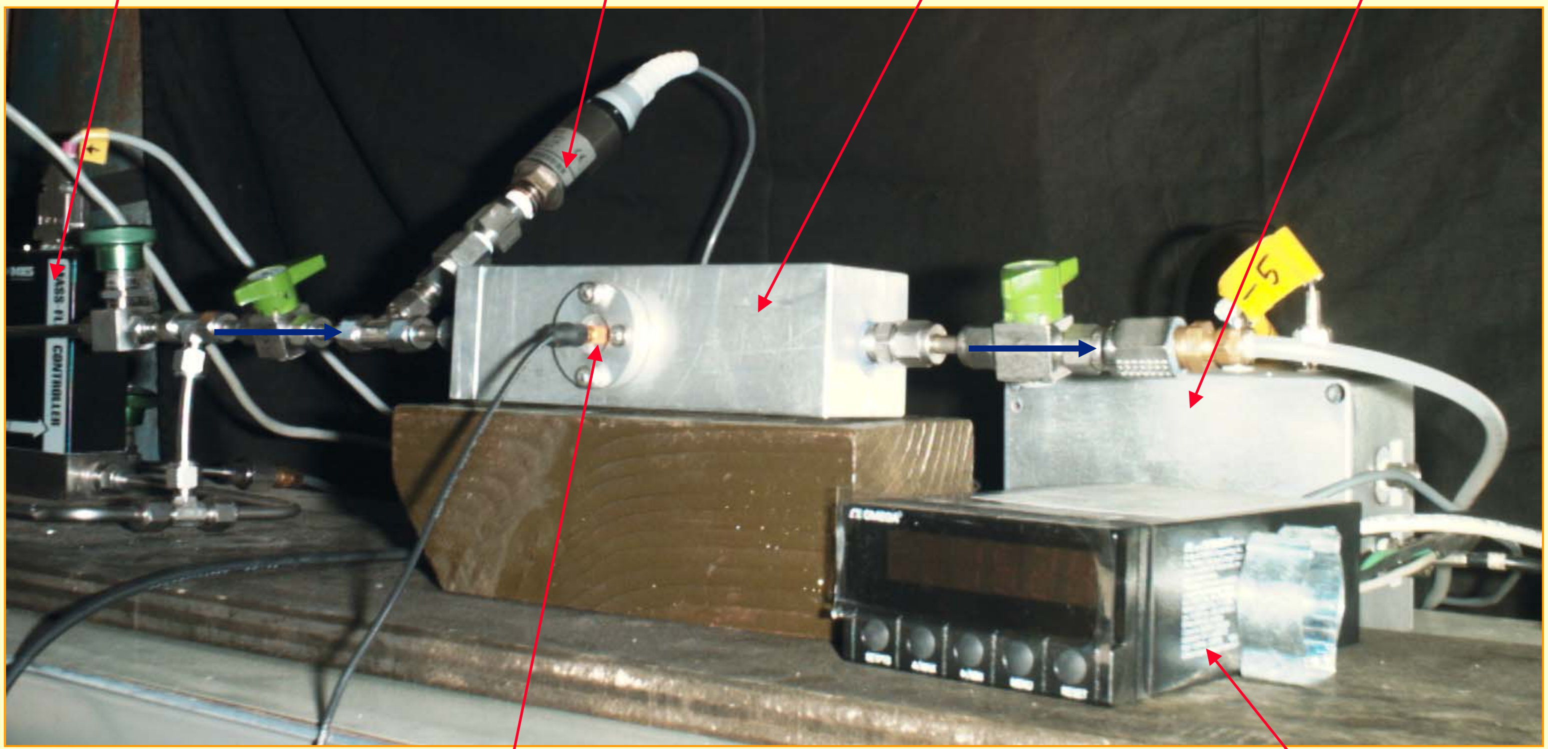
System Setup

Mass Flow Controller

Pressure Sensor

Gas Mixing Chamber

Dual-Channel Pre-amp



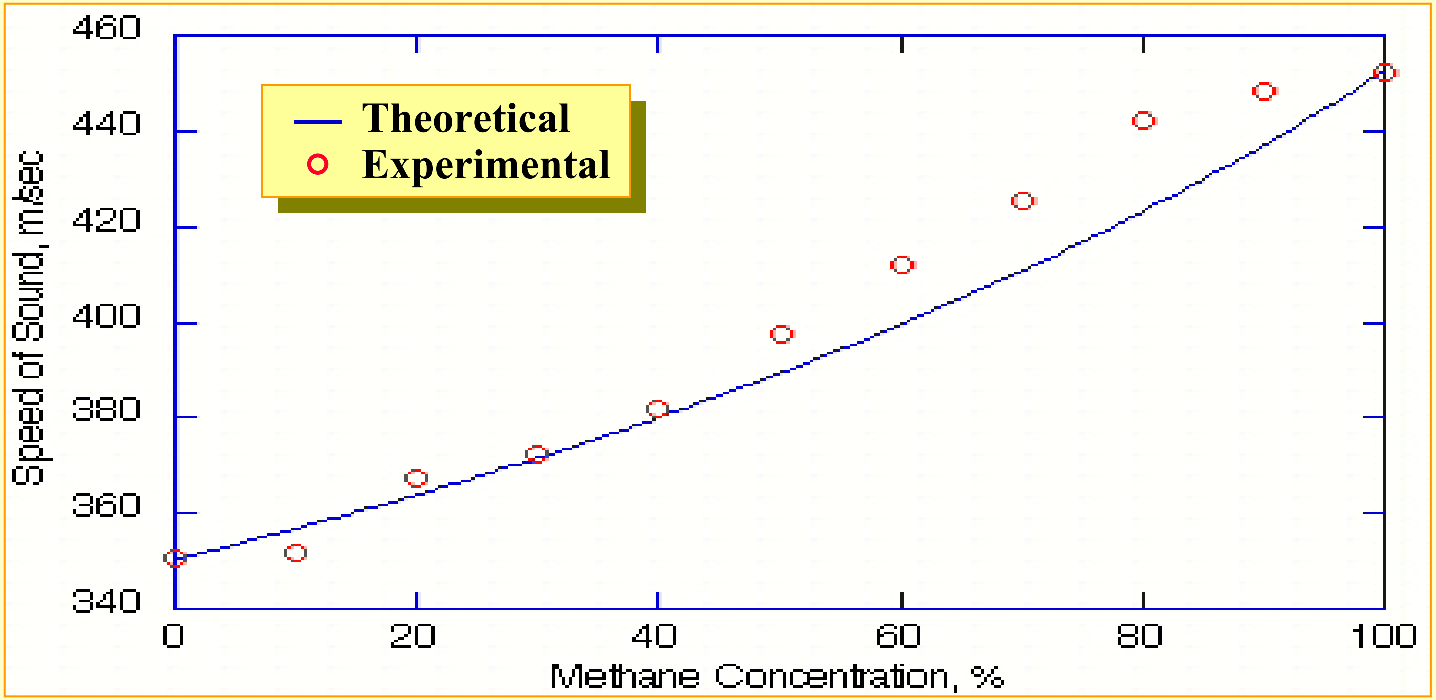
Transducer

Pressure Sensor Monitor

Engine Fuel Gas Composition (Illinois)

• Methane	92.6	%
• Ethane	3.4	
• Propane	0.6	
• C4+		
• Inerts		
• Butanes	0.2	
• Pentanes	0.1	
• Hexanes	0.1	
• O_2		
• CO_2	0.7	
• N_2	2.2	

Speed-of-Sound in a Gas Mixture (Methane/Nitrogen)



$$C=\left[\frac{RT}{\sum_{i=1}^{n} x_i M_i}\frac{\sum_{i=1}^{n} x_i C_{p_i}}{\sum_{i=1}^{n} x_i\left(C_{p_i}-R\right)}\right]^{1/2}$$

R: gas constant, T: absolute temperature

x_i: mole fraction of gas i

M_i: molecular weight of gas I

C_{pi}: heat capacity of constant pressure for gas i

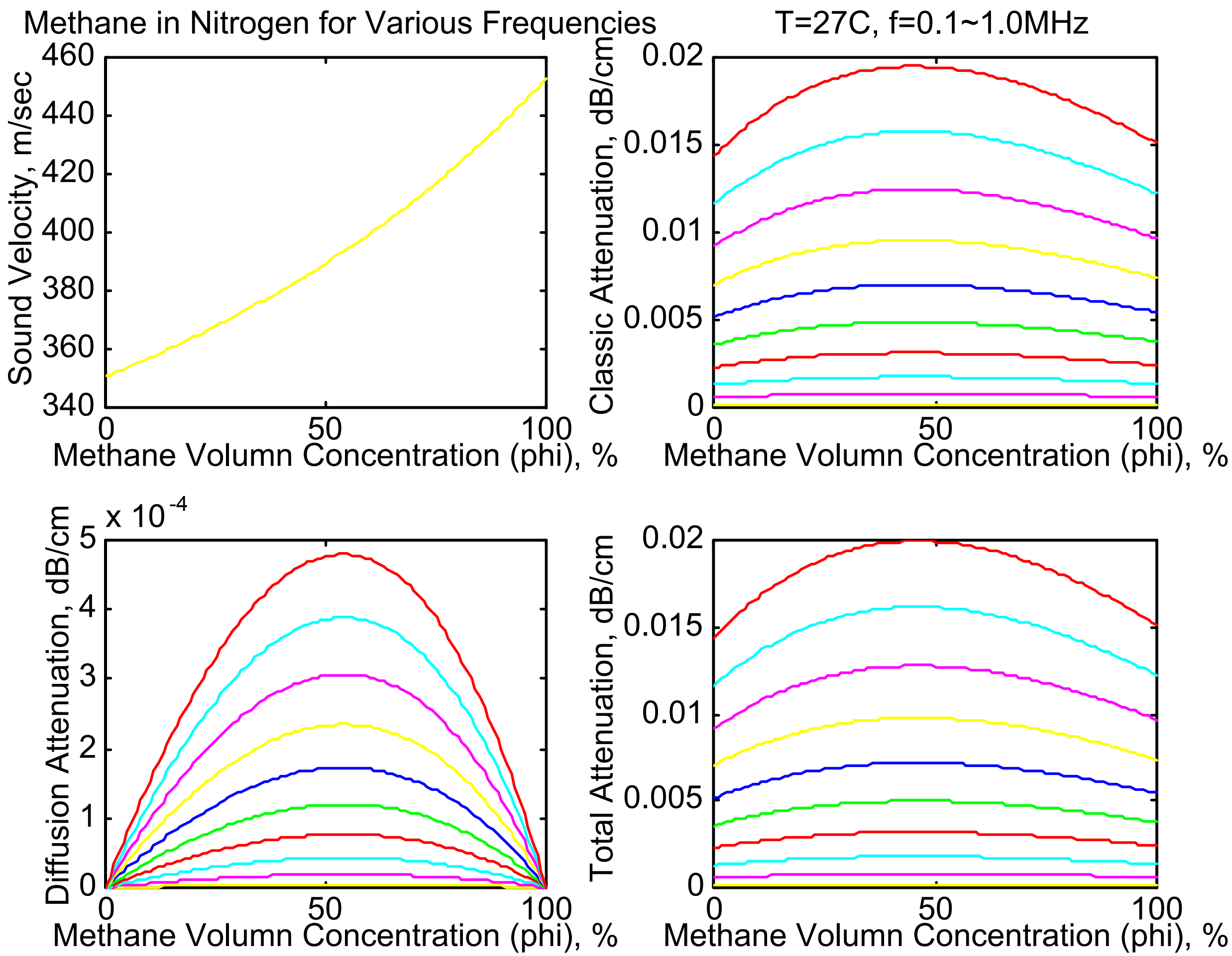
ARGONNE

Acoustic Attenuation in Gases

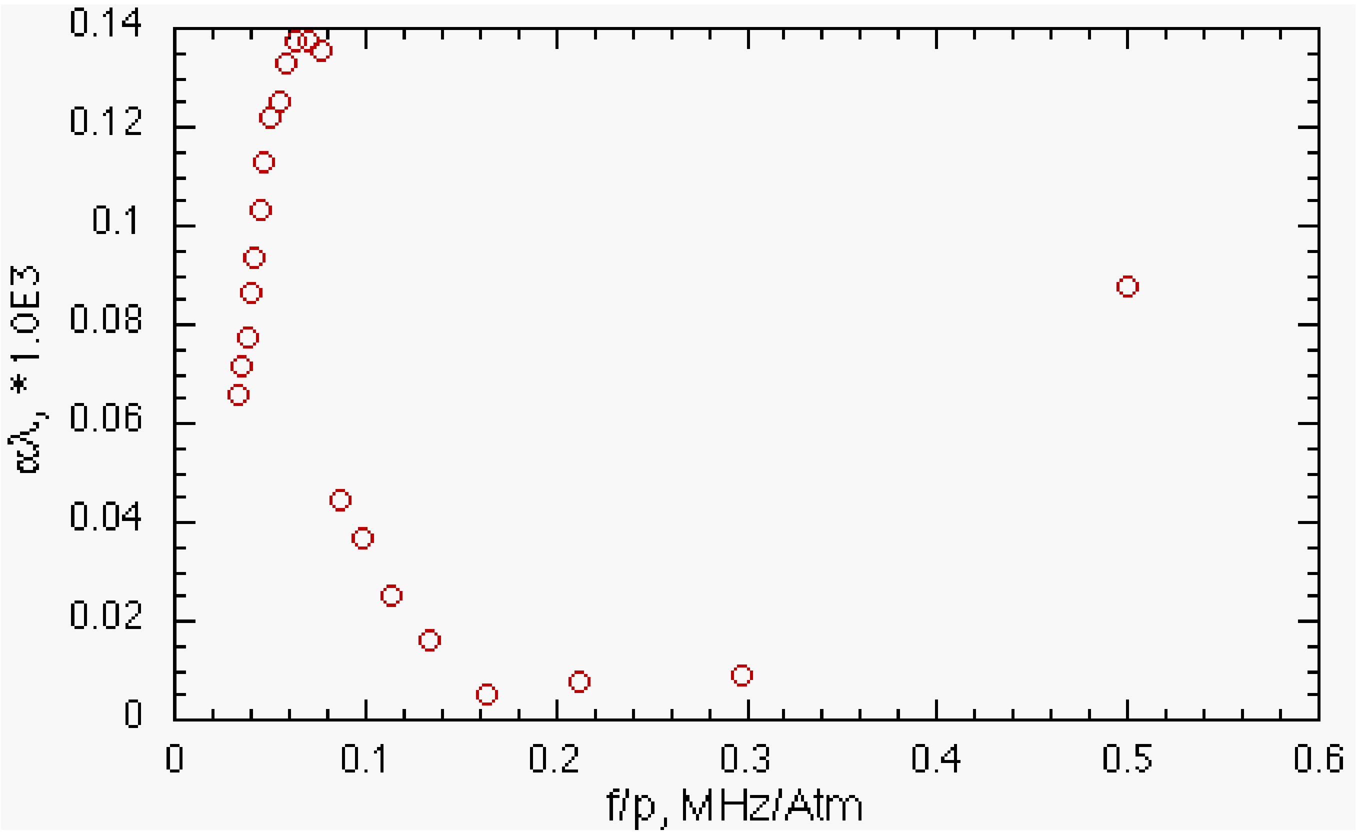
- Effects of viscosity and thermal conduction (classical attenuation) -- Proportional to f^2
- Diffusion effect -- Small effect in gas mixtures
- Acoustic relaxation effect -- Due to mainly vibrational relaxation of polyatomic molecules

Classical and Diffusion Attenuation

Methane in Nitrogen

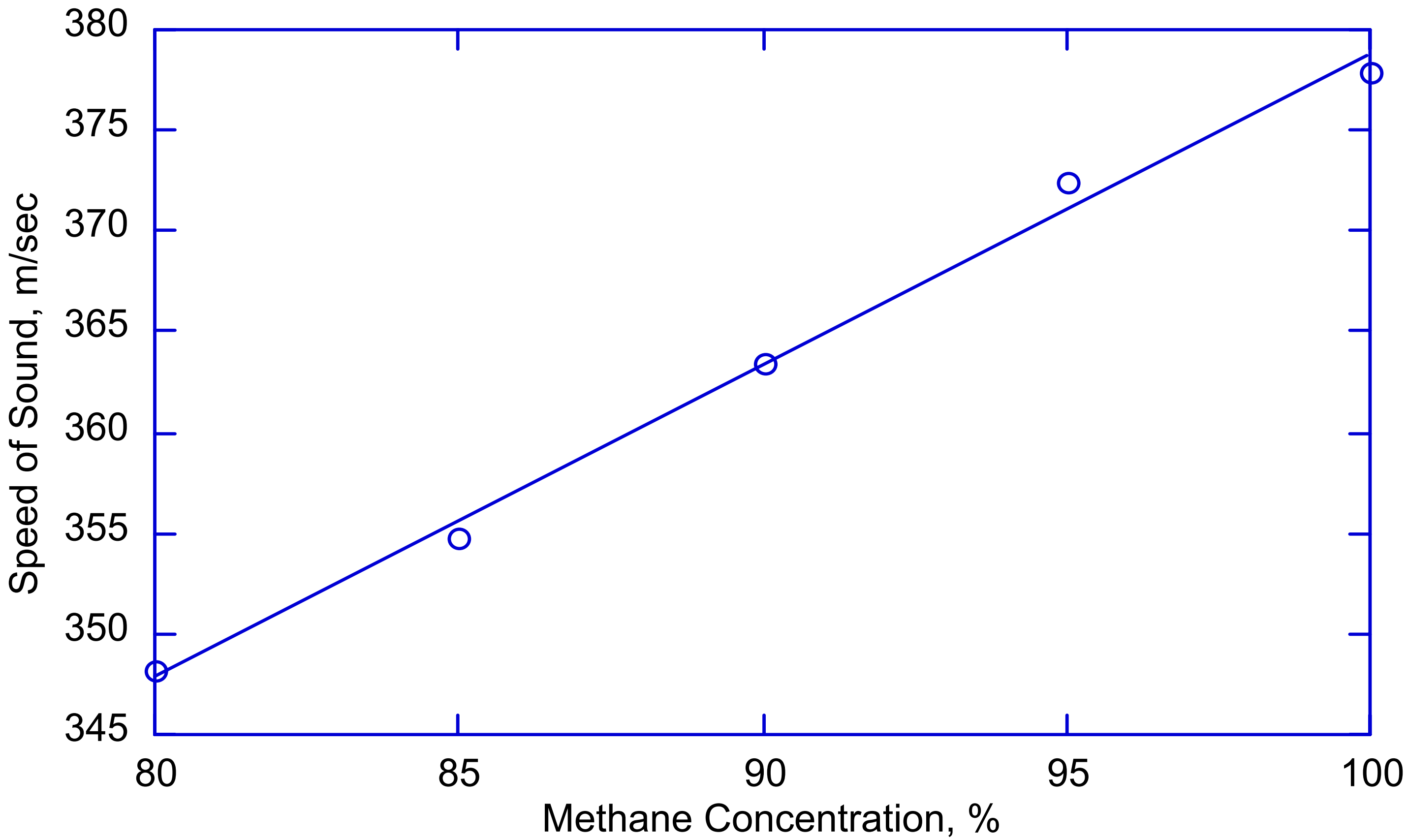


Relaxation Spectrum for 80% Methane in Nitrogen



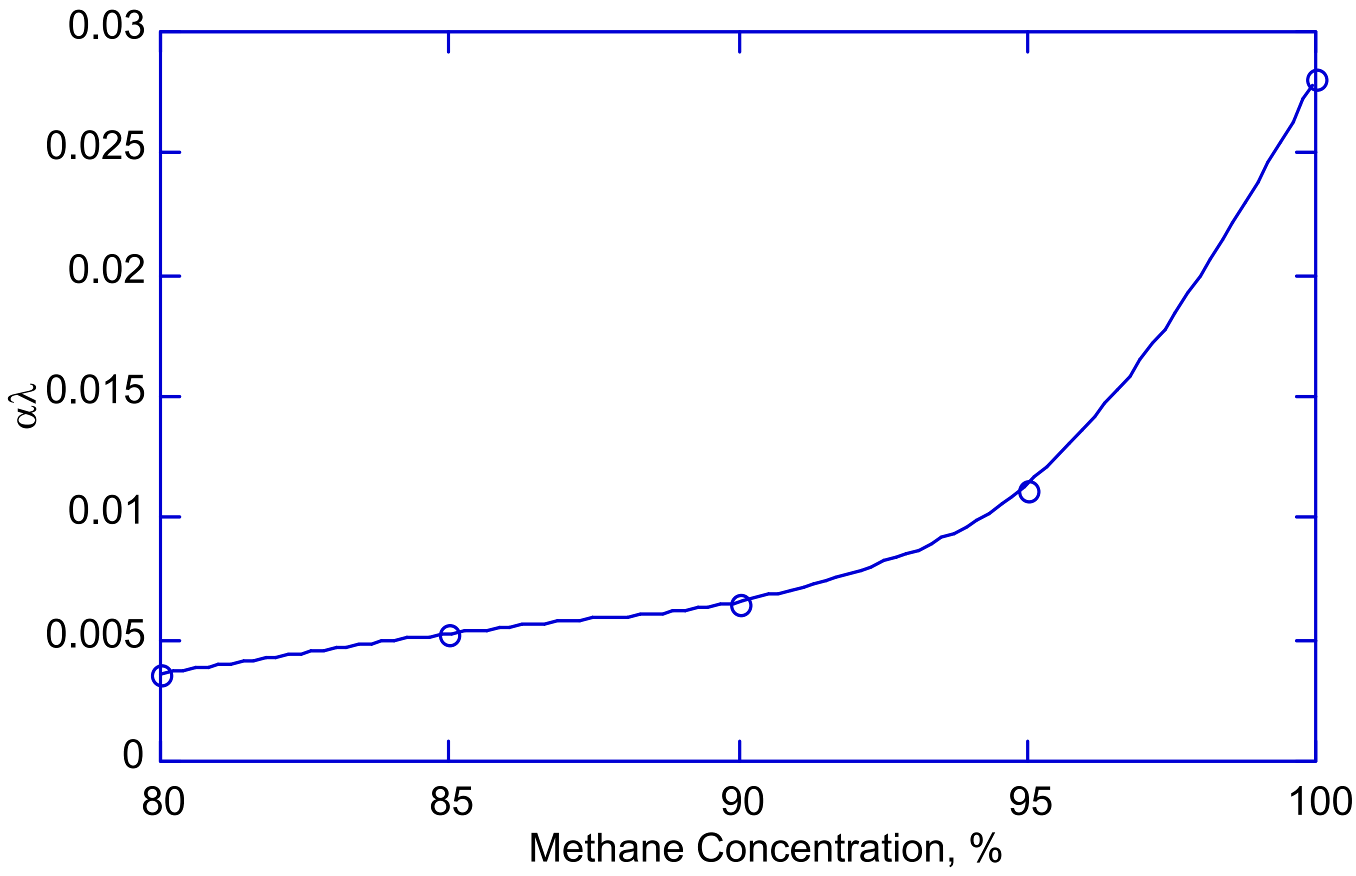
Ethane/Methane Mixtures

f/p = 4.9×10^4 Hz/atm, T = 77.6°F



Ethane/Methane Mixtures

f/p = 4.9x10^4 Hz/atm, T = 77.6^{o}F



Milestones Completed and Planned

- Milestones completed
  - Development of a quantum mechanic model for predicting acoustic relaxation of methane.
  - Evaluation of non-radioactive IMS sensor for detection of NO_x.
    - Developed a spark discharge negative ion source
    - Demonstrated the sensor capability to detect NO_x
    - Evaluated water-vapor effects and methods to reduce them
- Future plan
  - Develop and test acoustic natural-gas composition sensor
  - Develop field prototypes of IMS and acoustic sensors
  - Establish industrial partners for field testing of the sensors

Key Technical Barriers and Strategies to Overcome Them

- IMS key technical barriers
  - Moisture effect
  - Cross sensitivity
- Strategies
  - Engineering approach: Effective cooling, flow direction, etc.
  - Mobility resolution improvement: Drift tube design, ion-molecule chemistry, etc.
- Acoustic sensor key technical barriers:
  - Temperature and pressure effects
  - Wide-band transducer design
- Strategies
  - Establish a temperature and pressure calibration data base
  - Array transducer design

Typical ARES Engine Exhaust Composition

• Nitric Oxide	200 ppm
• H_2O	10 %
• Oxygen	9 %
• CO_2	5 %
• Hydrocarbons	650 ppm
• Methane	490 ppm
• CO	300 ppm
• Hydrogen	150 ppm
• Ethane	10 ppm
• Nitrogen	Balance

Project Risks

- The complexity (e.g., high voltage and high-sensitivity charge amplifier) and cost of the field IMS may be a risk.

- Acoustic sensor has no risk.

Impact on ARES

- ARES goals :To develop cleaner and more efficient next generation natural gas engines that will
  - Increase fuel combustion efficiency
  - Reduce emissions of NO_x, hydrocarbons, air toxics, and greenhouse gases
  - Reduce system costs and maintenance frequency
- Project impact on the goals:Reliable in-line sensors can provide continuous real-time monitoring of the combustion process and consequently improve the combustion efficiency.

Summary and Future Work

- Summary
  - IMS peak amplitude provides a measure of NO_x concentration (up to 500 ppm),
  - Both speed-of-sound and attenuation can be used to characterize fuel-gas composition (methane/ethane mixtures have been demonstrated).
- Future Work
  - Characterize fuel-gas acoustic relaxation spectra,
  - Develop a prototype acoustic fuel-vapor sensor,
  - Develop a prototype IMS sensor,
  - Conduct of Field tests.